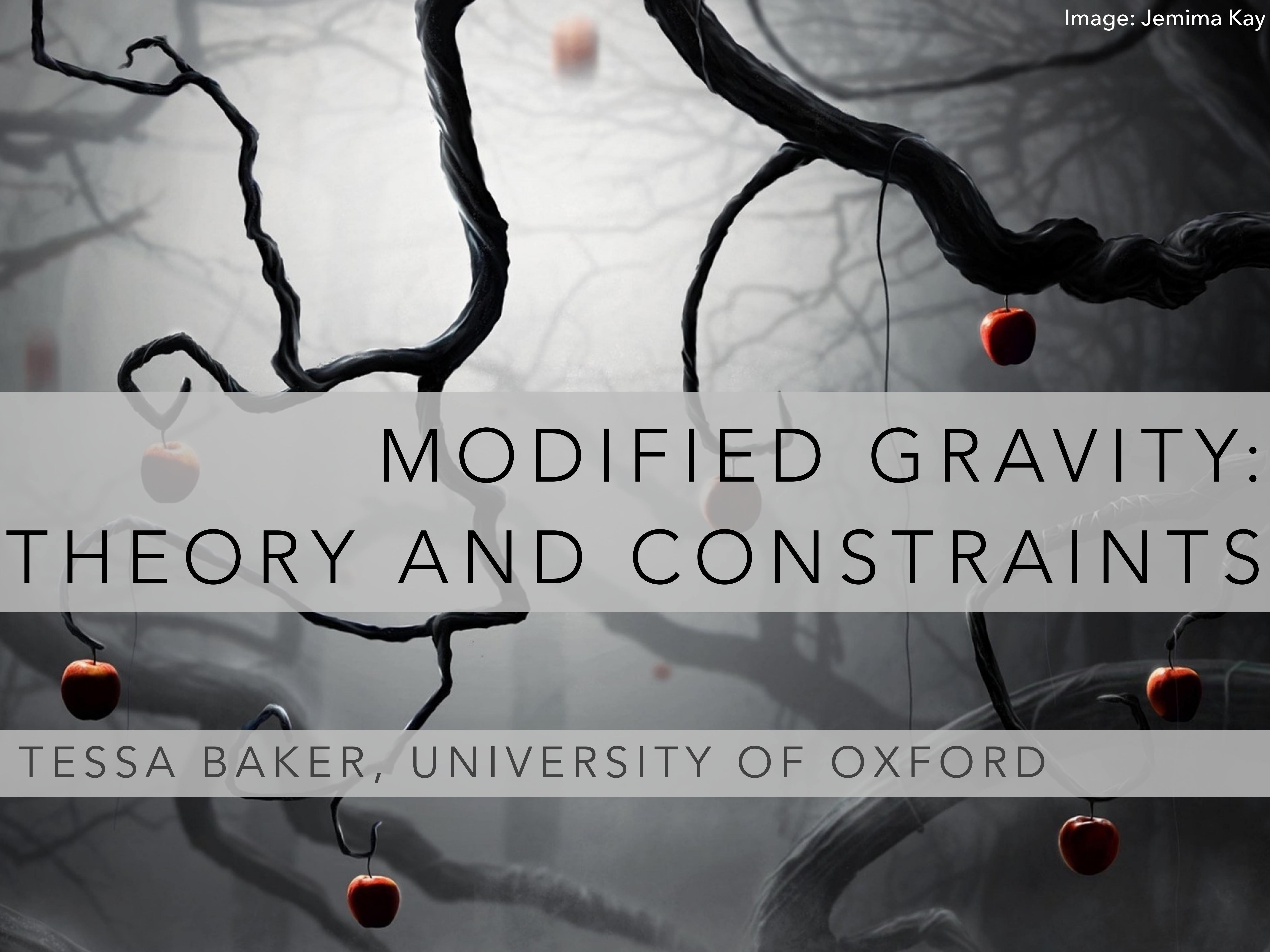

Image: Jemima Kay

MODIFIED GRAVITY: THEORY AND CONSTRAINTS

TESSA BAKER, UNIVERSITY OF OXFORD

OUTLINE

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- The landscape of modified gravity.

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- Parameterised frameworks for testing GR.

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- The landscape of modified gravity.
- Parameterised frameworks for testing GR.
- Current and future constraints.

Image: Bob Hutchins

1. THE GRAVITY LANDSCAPE

WHY TEST GRAVITY?

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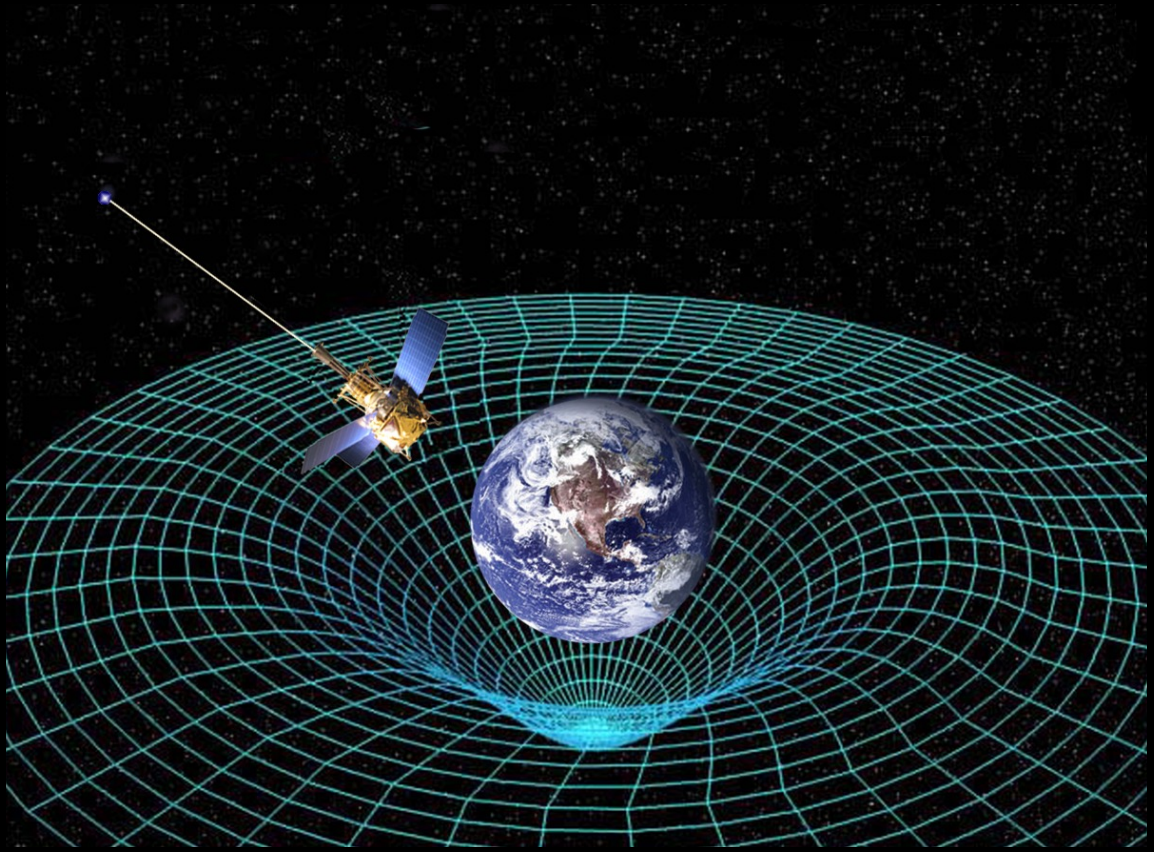
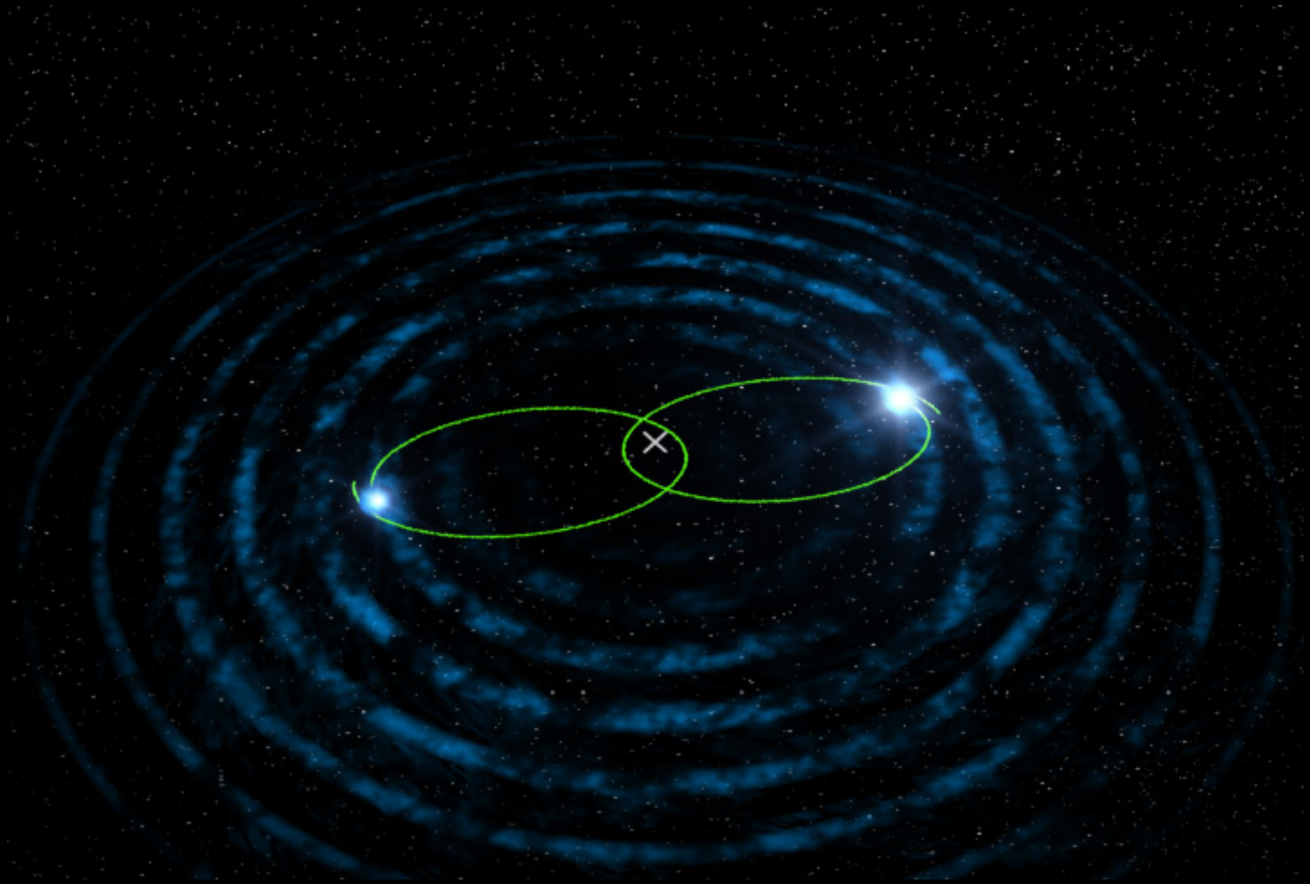




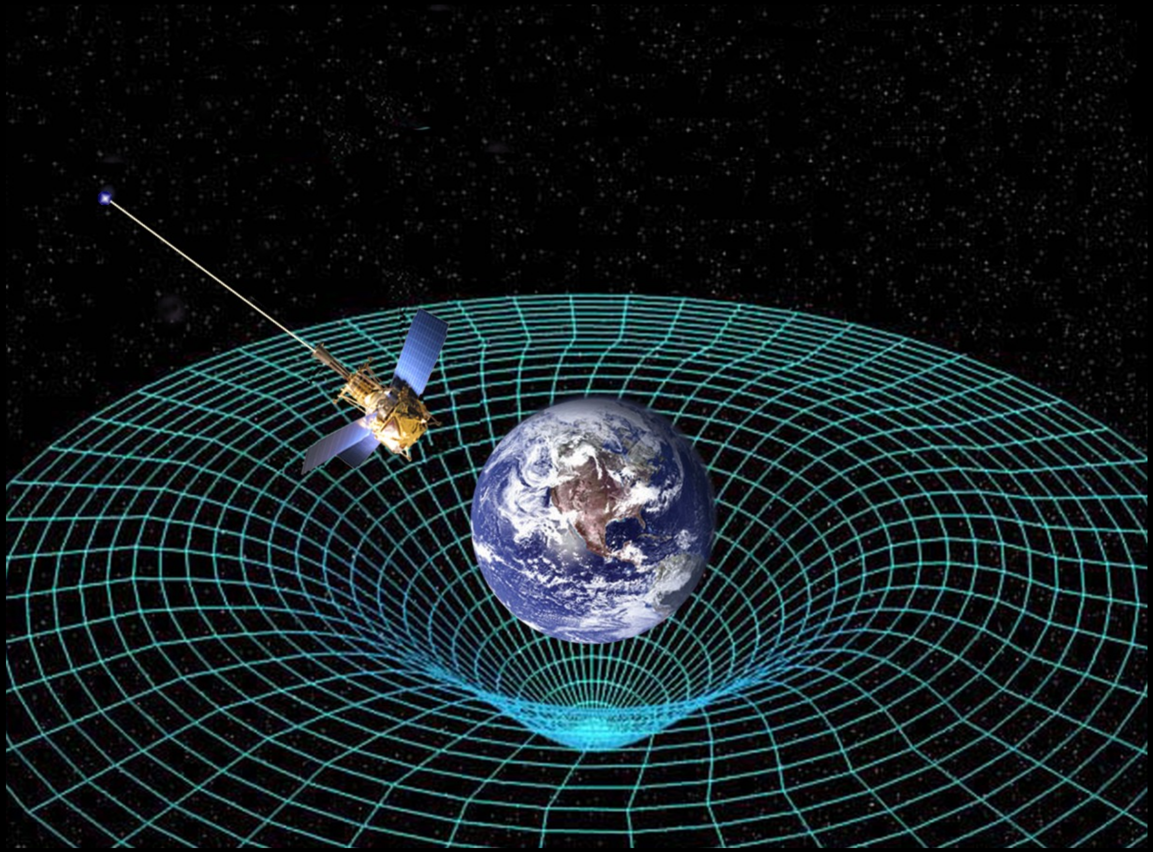
Images: NASA, Norbert Bartel.

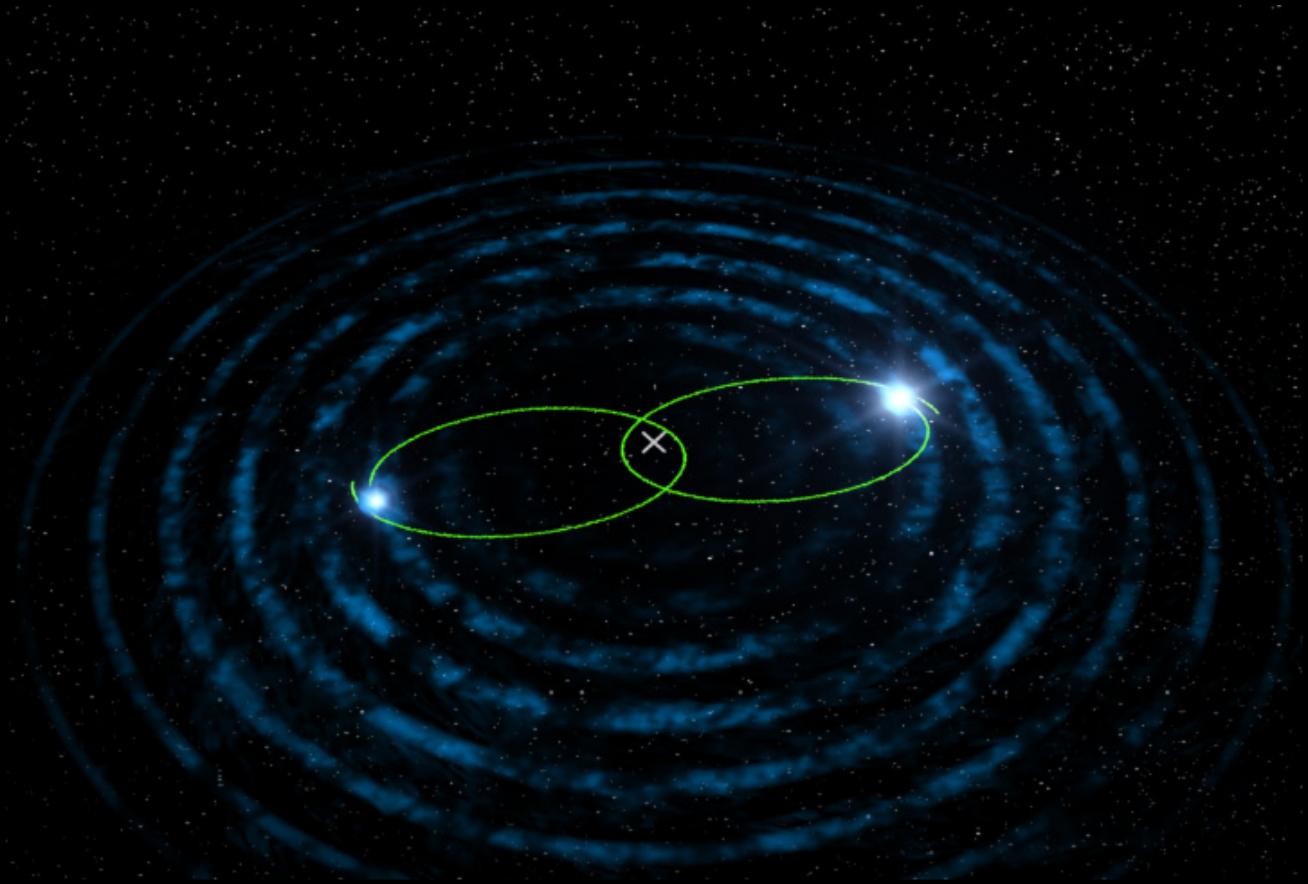
WHY TEST GRAVITY?

- Cosmic acceleration, i.e. dark energy.

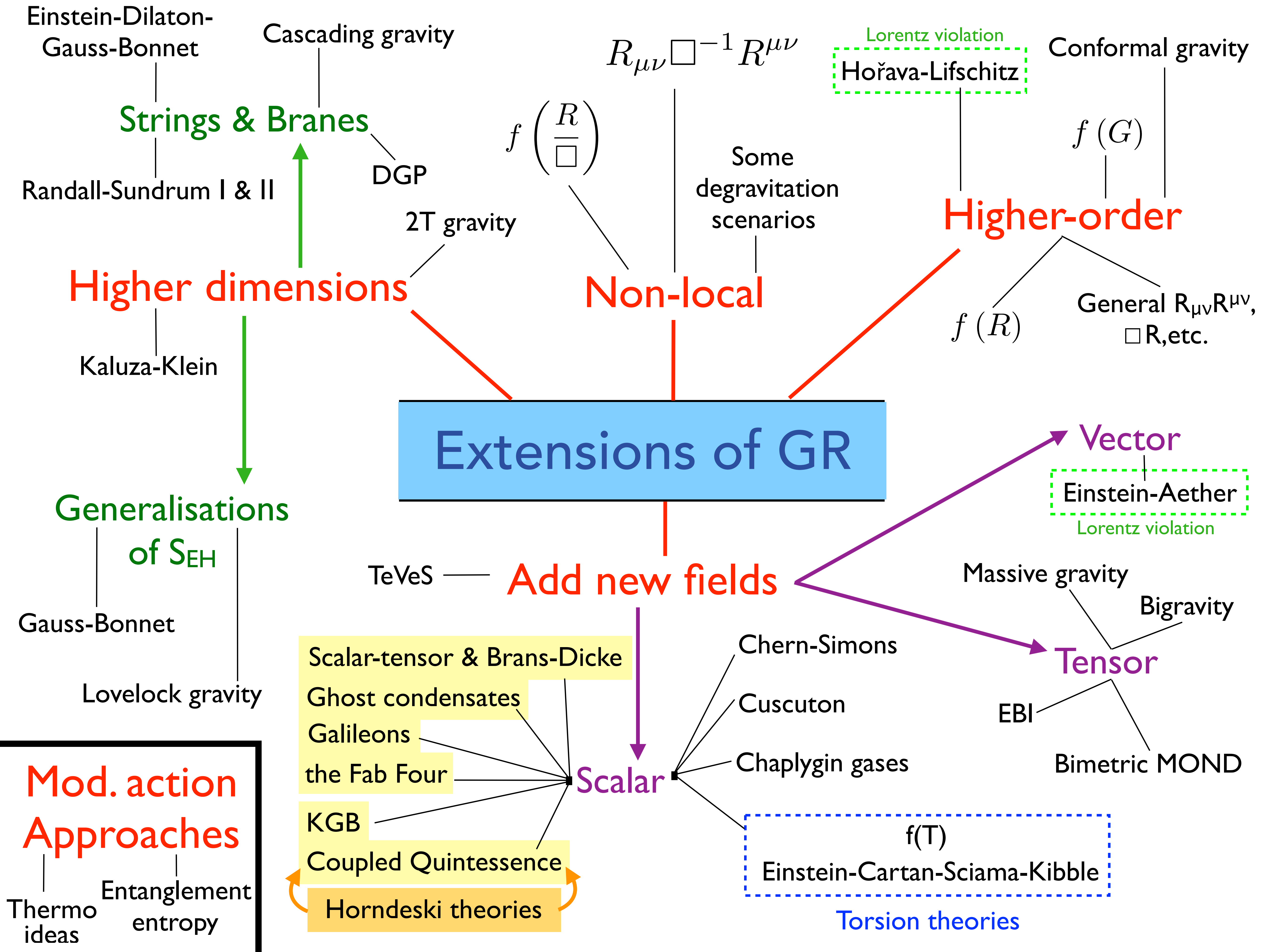
- Cosmological scales >> scales of precision tests.

- Fifth forces on astrophysical scales are poorly constrained.





Images: NASA, Norbert Bartel.



Extensions of GR

Higher dimensions

Strings & Branes

Einstein-Dilaton-Gauss-Bonnet

Cascading gravity

Randall-Sundrum I & II

DGP

2T gravity

Kaluza-Klein

Generalisations of S_{EH}

Gauss-Bonnet

Lovelock gravity

Non-local

$f\left(\frac{R}{\Box}\right)$

$R_{\mu\nu}\Box^{-1}R^{\mu\nu}$

Some degravitation scenarios

Higher-order

Lorentz violation

Hořava-Lifschitz

Conformal gravity

$f\left(G\right)$

$f\left(R\right)$

General $R_{\mu\nu}R^{\mu\nu}$, $\Box R$,etc.

Add new fields

TeVeS

Vector

Einstein-Aether

Lorentz violation

Tensor

Massive gravity

Bigravity

EBI

Bimetric MOND

Scalar

Scalar-tensor & Brans-Dicke

Ghost condensates

Galileons

the Fab Four

KGB

Coupled Quintessence

Horndeski theories

Chern-Simons

Cuscuton

Chaplygin gases

f(T)

Einstein-Cartan-Sciama-Kibble

Torsion theories

Mod. action Approaches

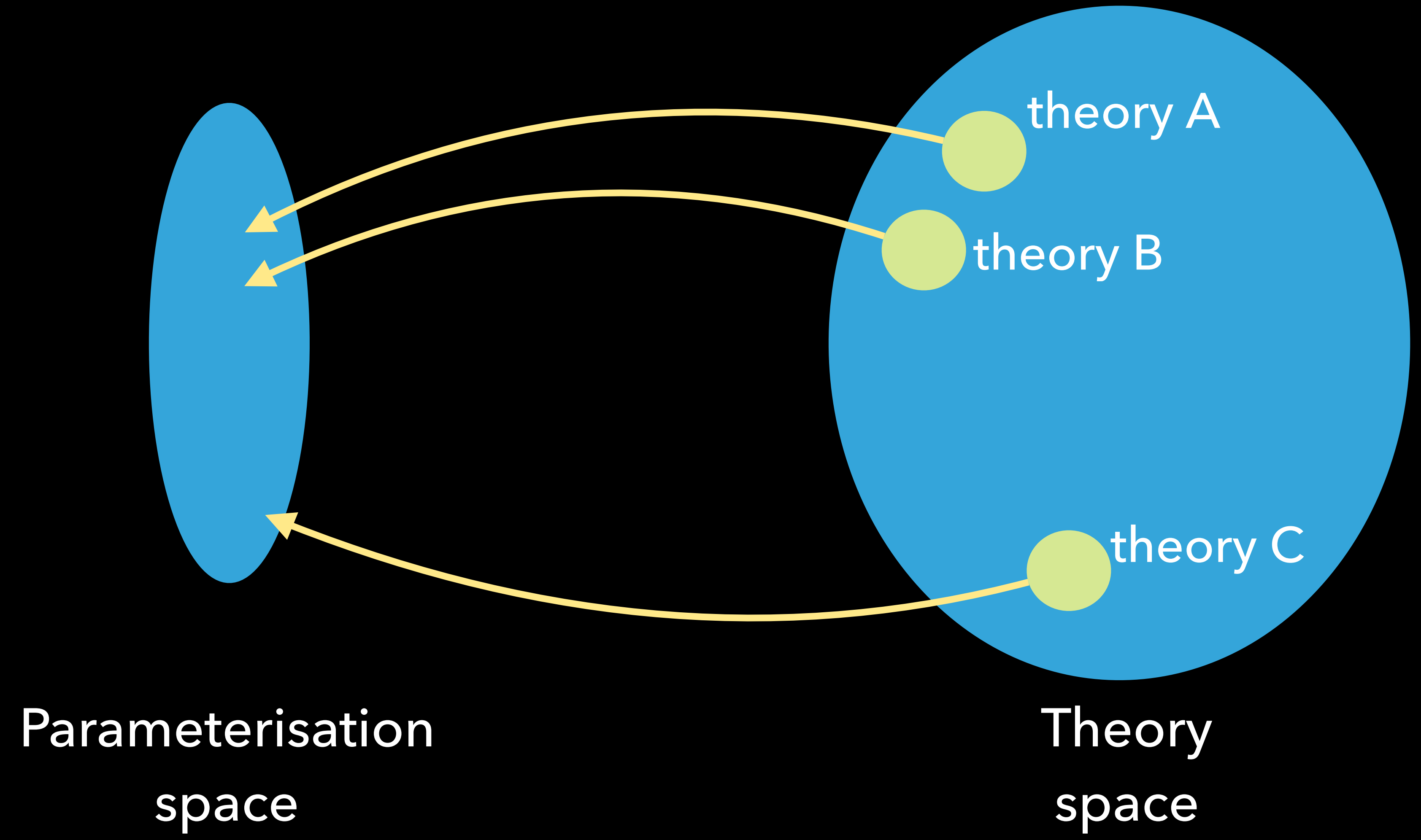
Thermo ideas

Entanglement entropy


Image: Tom Barrett

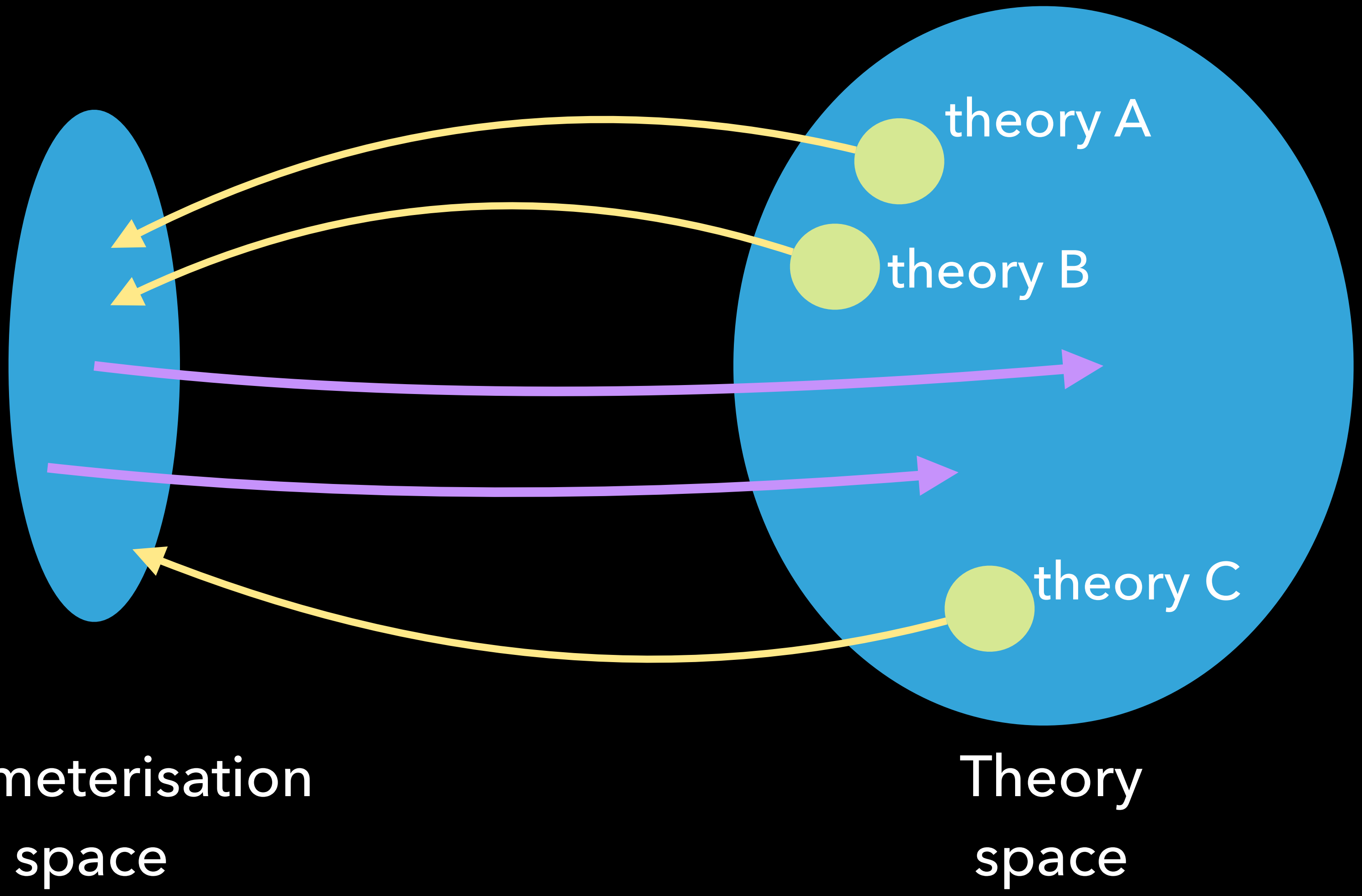
2. PARAMETERISED METHODS FOR TESTING GR

PARAMETERISING GRAVITY



Gleyzes, Langlois & Vernizzi (2014)
Lagos, Baker ++ (2016)

PARAMETERISING GRAVITY



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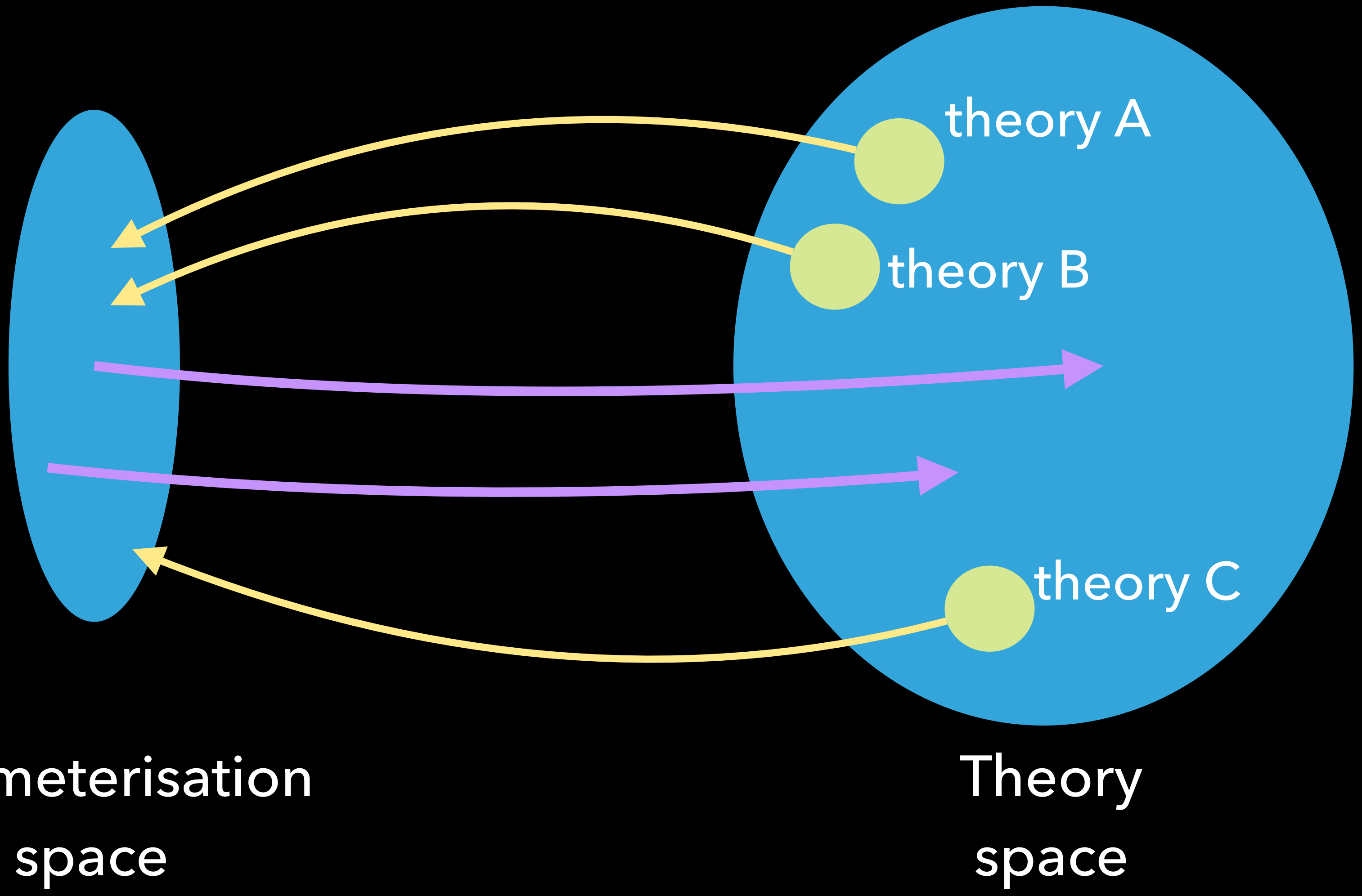

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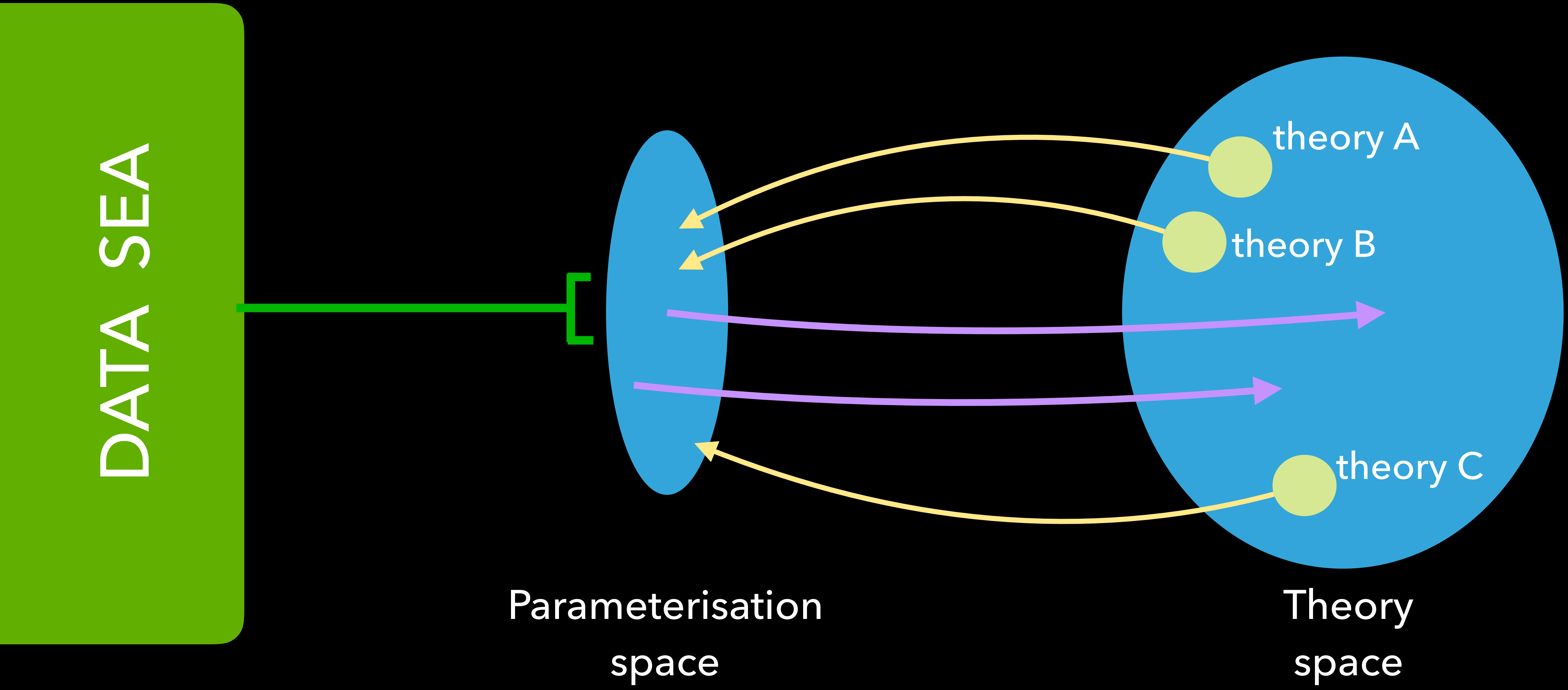

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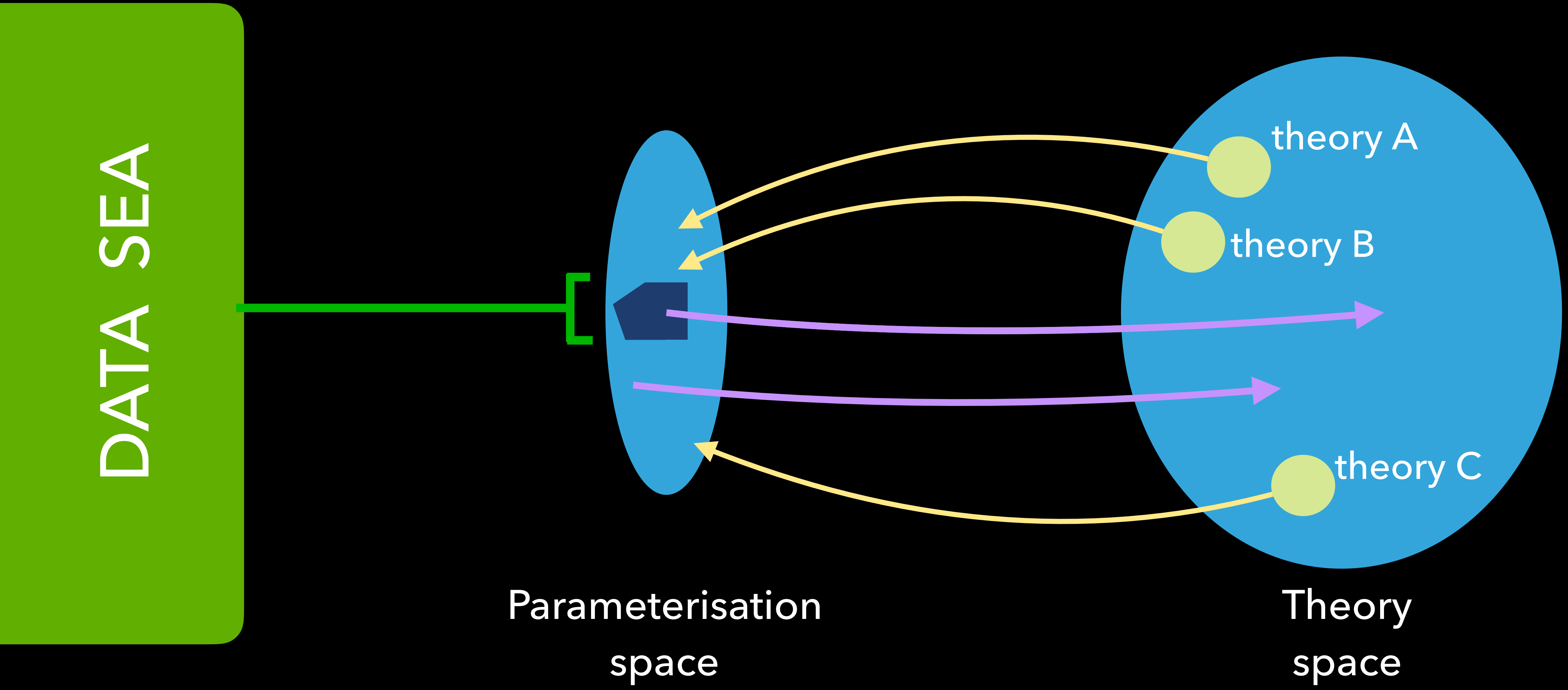

DATA SEA

theory A

theory B

theory C

Parameterisation
space

Theory
space

Gleyzes, Langlois & Vernizzi (2014)
Lagos, Baker ++ (2016)

EFT-STYLE APPROACHES

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$$L \simeq \bar{L} + L_{\Theta_a}\,\delta\Theta_a + \frac{1}{2}\,L_{\Theta_a\Theta_b}\delta\Theta_a\delta\Theta_b + \ldots$$

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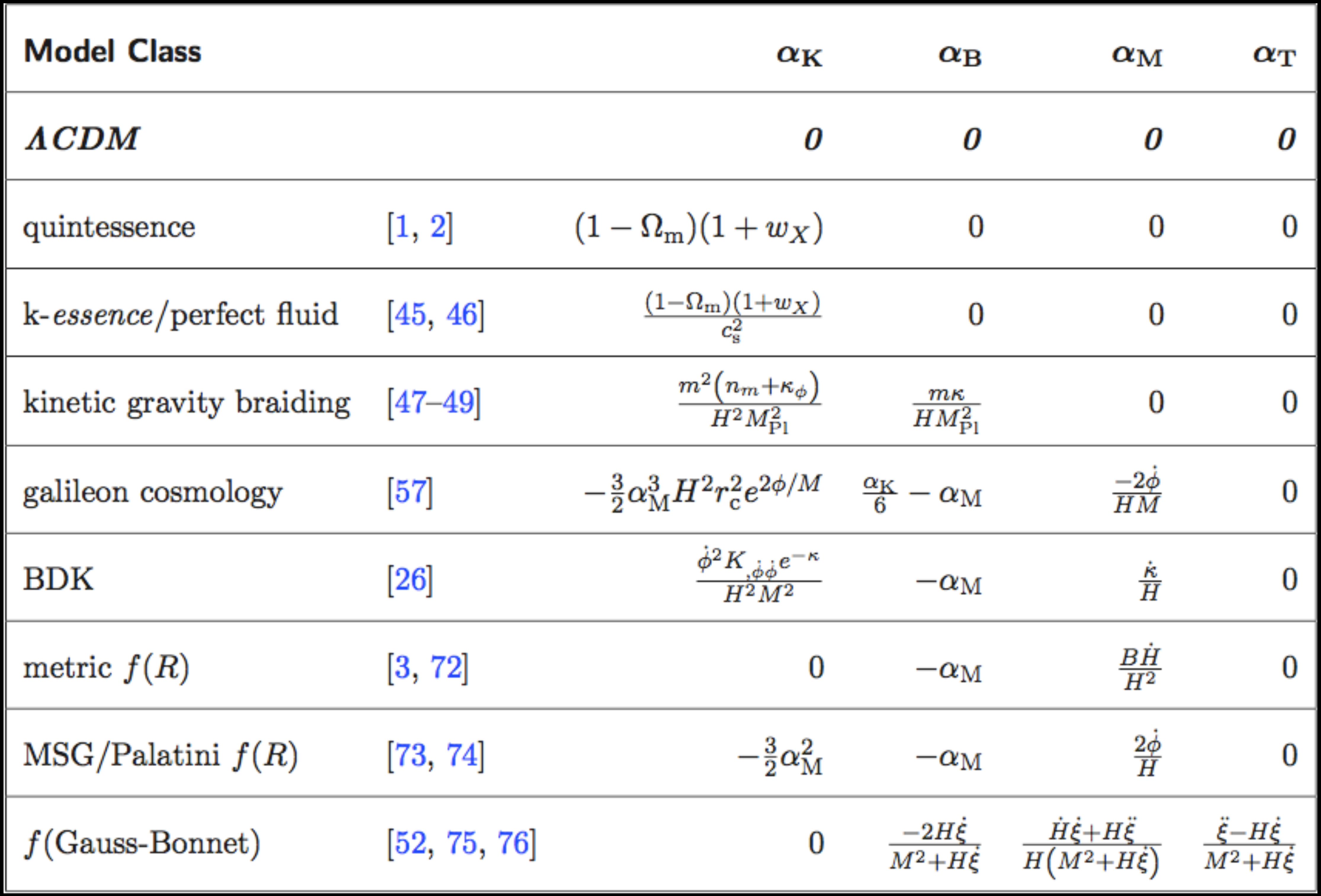

Model Class		α_K	α_B	α_M	α_T
ΛCDM		***0***	***0***	***0***	***0***
quintessence	[1, 2]	$(1-\Omega_\mathrm{m})(1+w_X)$	0	0	0
k-*essence*/perfect fluid	[45, 46]	$\frac{(1-\Omega_\mathrm{m})(1+w_X)}{c_\mathrm{s}^2}$	0	0	0
kinetic gravity braiding	[47–49]	$\frac{m^2\left(n_m+\kappa_\phi\right)}{H^2 M_\mathrm{Pl}^2}$	$\frac{m\kappa}{H M_\mathrm{Pl}^2}$	0	0
galileon cosmology	[57]	$-\frac{3}{2}\alpha_\mathrm{M}^3 H^2 r_\mathrm{c}^2 e^{2\phi/M}$	$\frac{\alpha_\mathrm{K}}{6}-\alpha_\mathrm{M}$	$\frac{-2\dot{\phi}}{HM}$	0
BDK	[26]	$\frac{\dot{\phi}^2 K_{,\dot{\phi}\dot{\phi}} e^{-\kappa}}{H^2 M^2}$	$-\alpha_\mathrm{M}$	$\frac{\dot{\kappa}}{H}$	0
metric $f(R)$	[3, 72]	0	$-\alpha_\mathrm{M}$	$\frac{B\dot{H}}{H^2}$	0
MSG/Palatini $f(R)$	[73, 74]	$-\frac{3}{2}\alpha_\mathrm{M}^2$	$-\alpha_\mathrm{M}$	$\frac{2\dot{\phi}}{H}$	0
f(Gauss-Bonnet)	[52, 75, 76]	0	$\frac{-2H\dot{\xi}}{M^2+H\dot{\xi}}$	$\frac{\dot{H}\dot{\xi}+H\ddot{\xi}}{H\left(M^2+H\dot{\xi}\right)}$	$\frac{\ddot{\xi}-H\dot{\xi}}{M^2+H\dot{\xi}}$

Bellini & Sawicki (2014)

Image: Allen Cai

3. DATA — CURRENT & FUTURE

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Creminelli & Vernizzi 1710.05877
Sakstein & Jain 1710.05893
Ezquiaga & Zuma. 1710.05901
TB++ 1710.06394

GW170817 & GRB 170817A

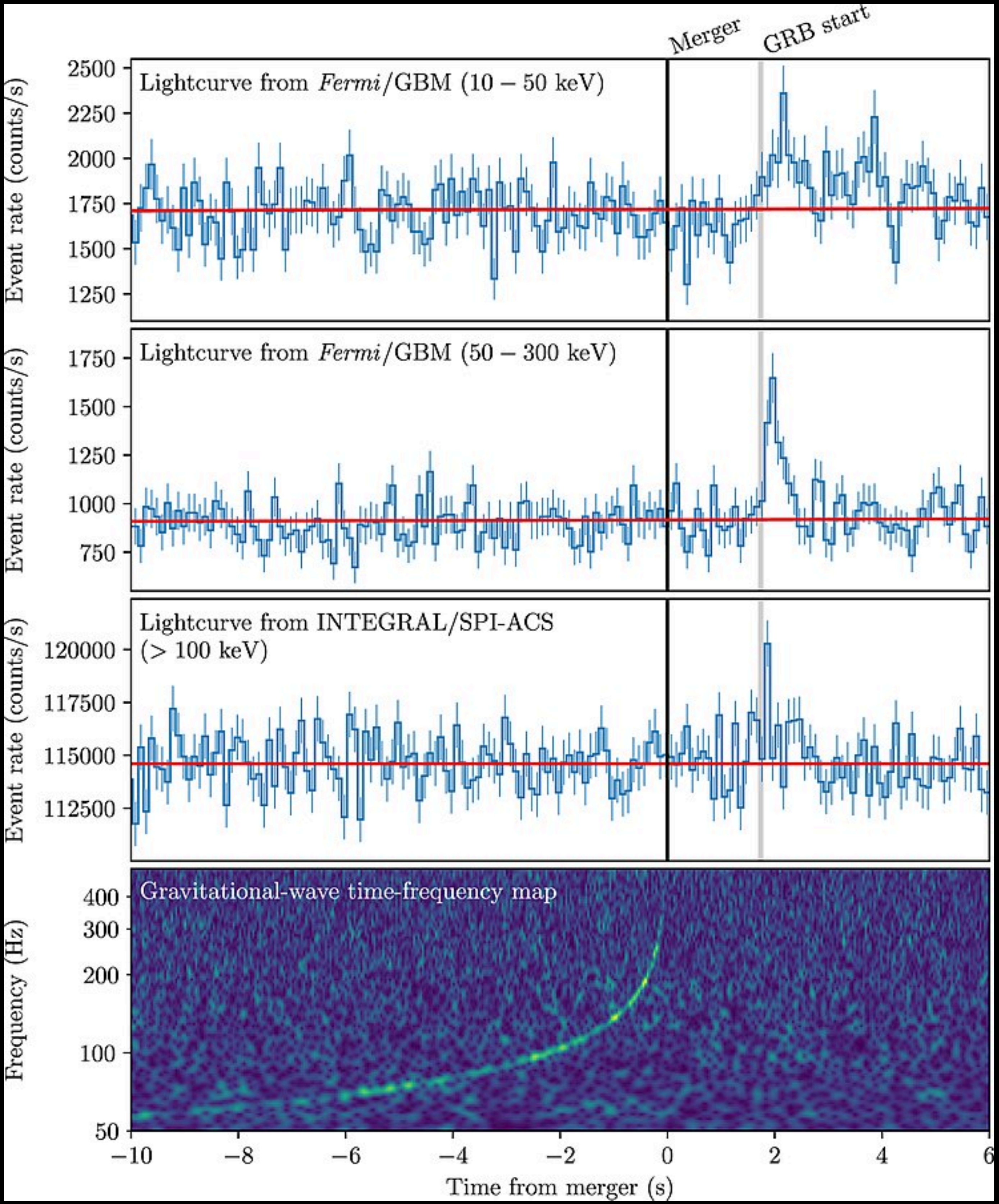

Image: LIGO-VIRGO Collaboration.

$$c_T^2 = 1 + \alpha_T$$

GW170817 & GRB 170817A

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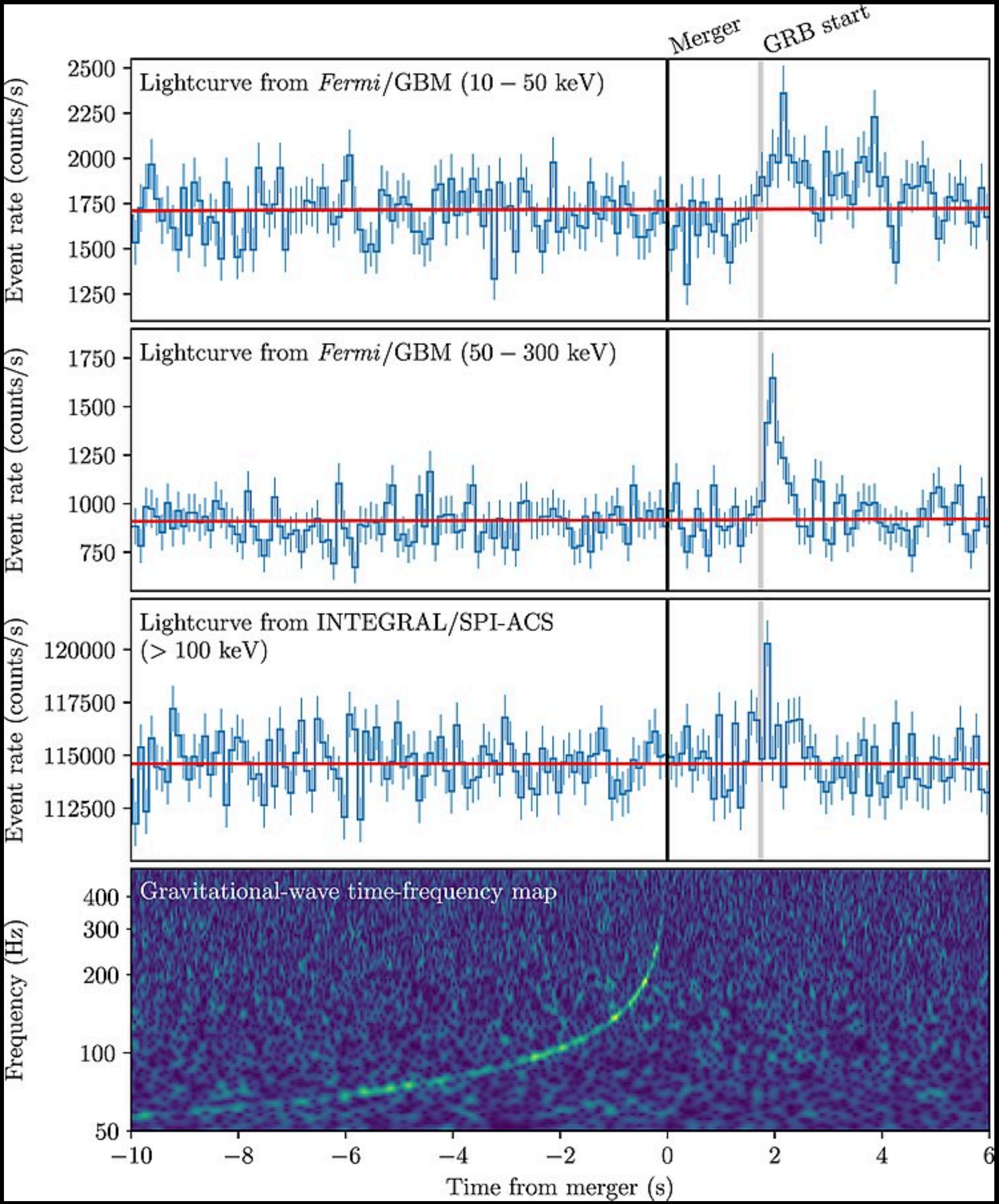

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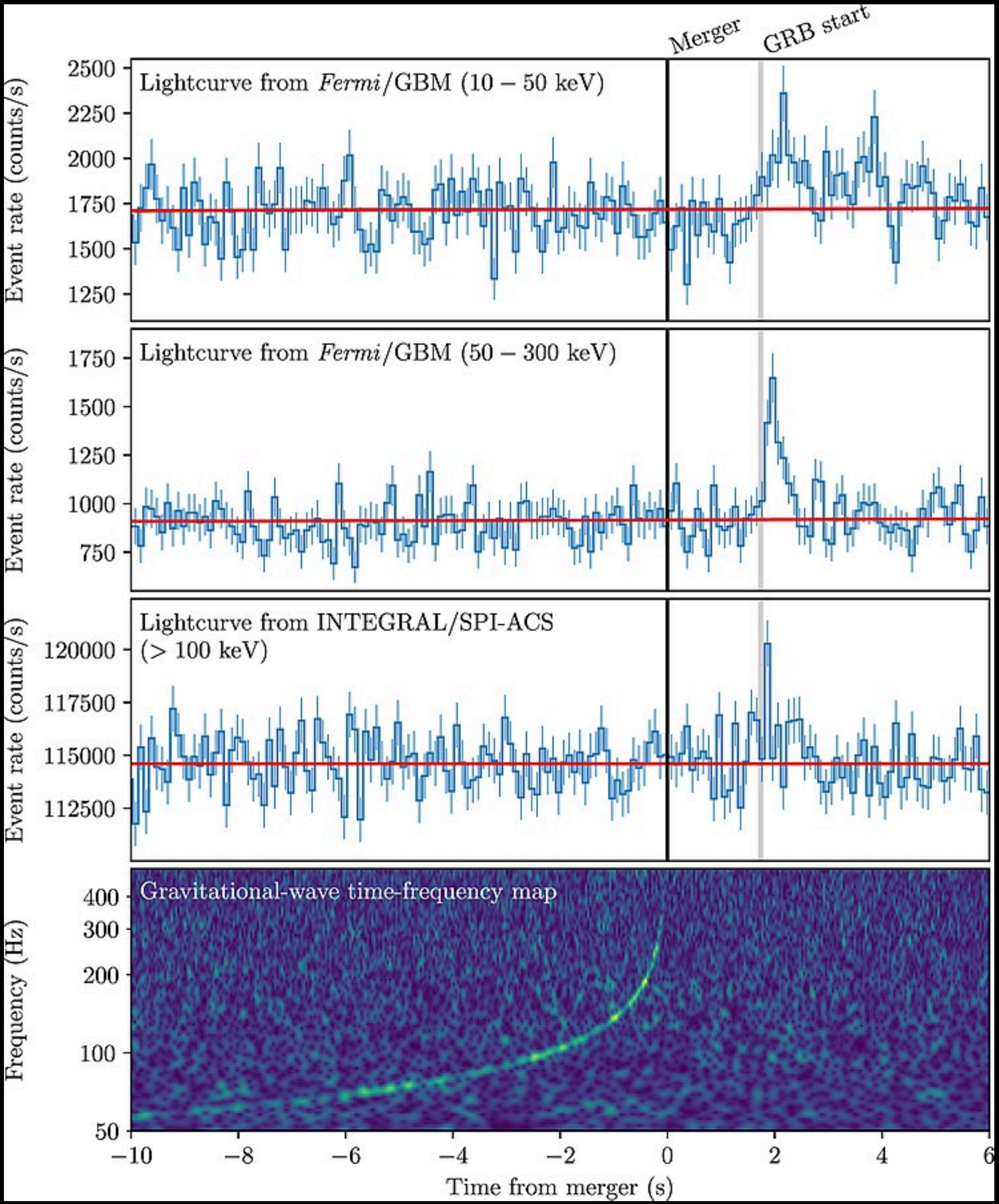

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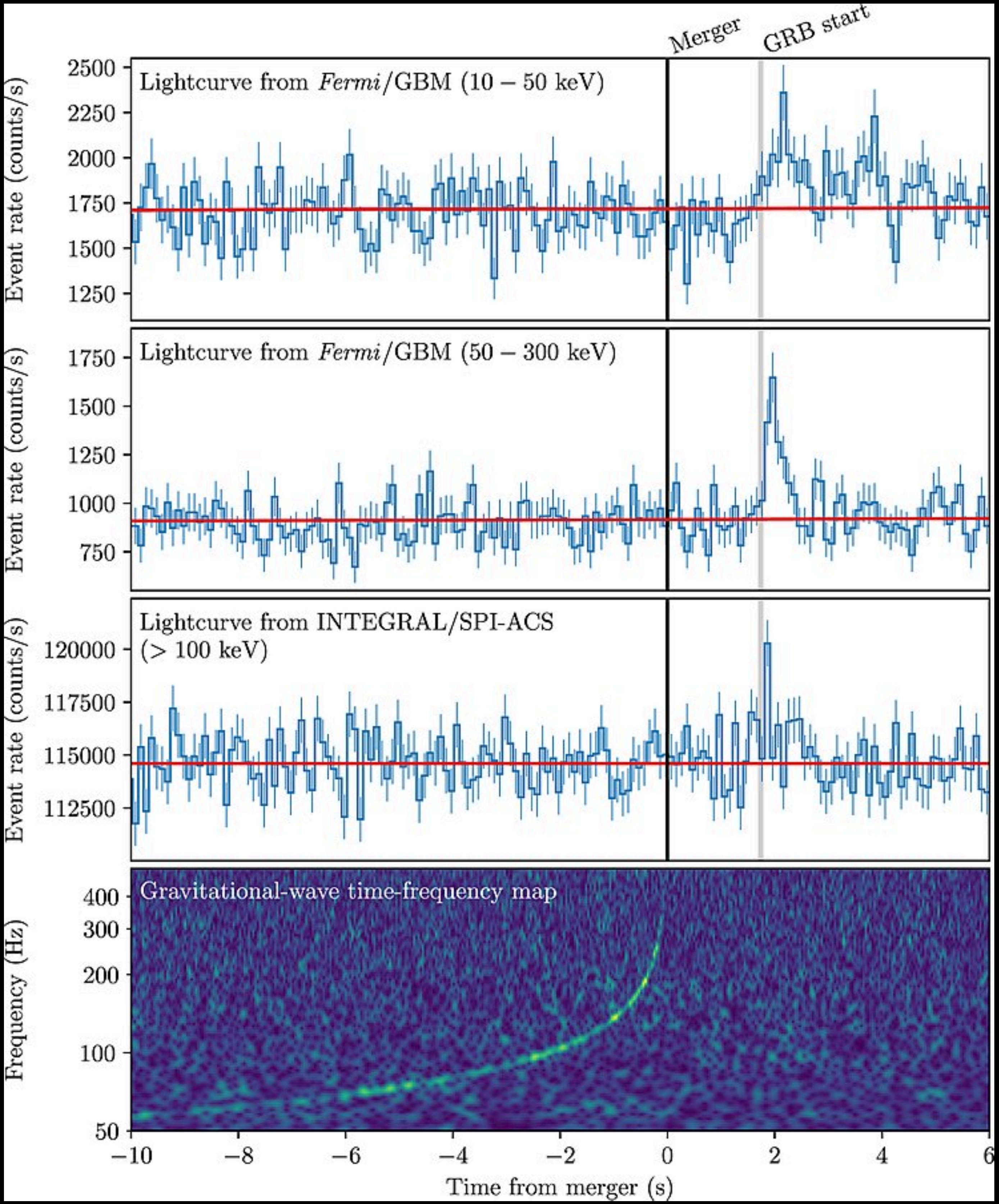

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!! c. f. $|\alpha_M|, |\alpha_B| \lesssim \mathcal{O}(1)$

GW170817 & GRB 170817A

What does this mean for gravity theories?

GW170817 & GRB 170817A

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Scalar case clearest; full theory is **Horndeski gravity**.

$$S = \int d^4x \sqrt{-g}\ \Sigma_{i=2}^{5}\, \mathcal{L}_i + S_M$$

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$$\mathcal{L}_5 = G_5 G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{1}{6}G_{5,X}\big\{(\nabla\phi)^3 - 3\nabla^\mu\nabla^\nu\phi\nabla_\mu\nabla_\nu\phi\Box\phi + 2\nabla^\nu\nabla_\mu\phi\nabla^\alpha\nabla_\nu\phi\nabla^\mu\nabla_\alpha\phi\big\}$$

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where $G_i = G_i(\phi, X)$ and $X = -\nabla_\nu \phi \nabla^\nu \phi / 2$.

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Linearised theory maps to alpha parameters:

$$\Rightarrow\ \alpha_T(t) = \frac{2X}{M_*^2}\left[2G_{4,X} - 2G_{5,\phi} - \left(\ddot{\phi} - \dot{\phi}H\right)G_{5,X}\right]$$

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Vector-tensor theories are a little bruised, but survive.

$$\mathcal{L}_4 \propto R \qquad\qquad \mathcal{L}_5 \propto G_{\mu\nu}\nabla^{\mu}A^{\nu}$$

(+ Maxwell term etc.)

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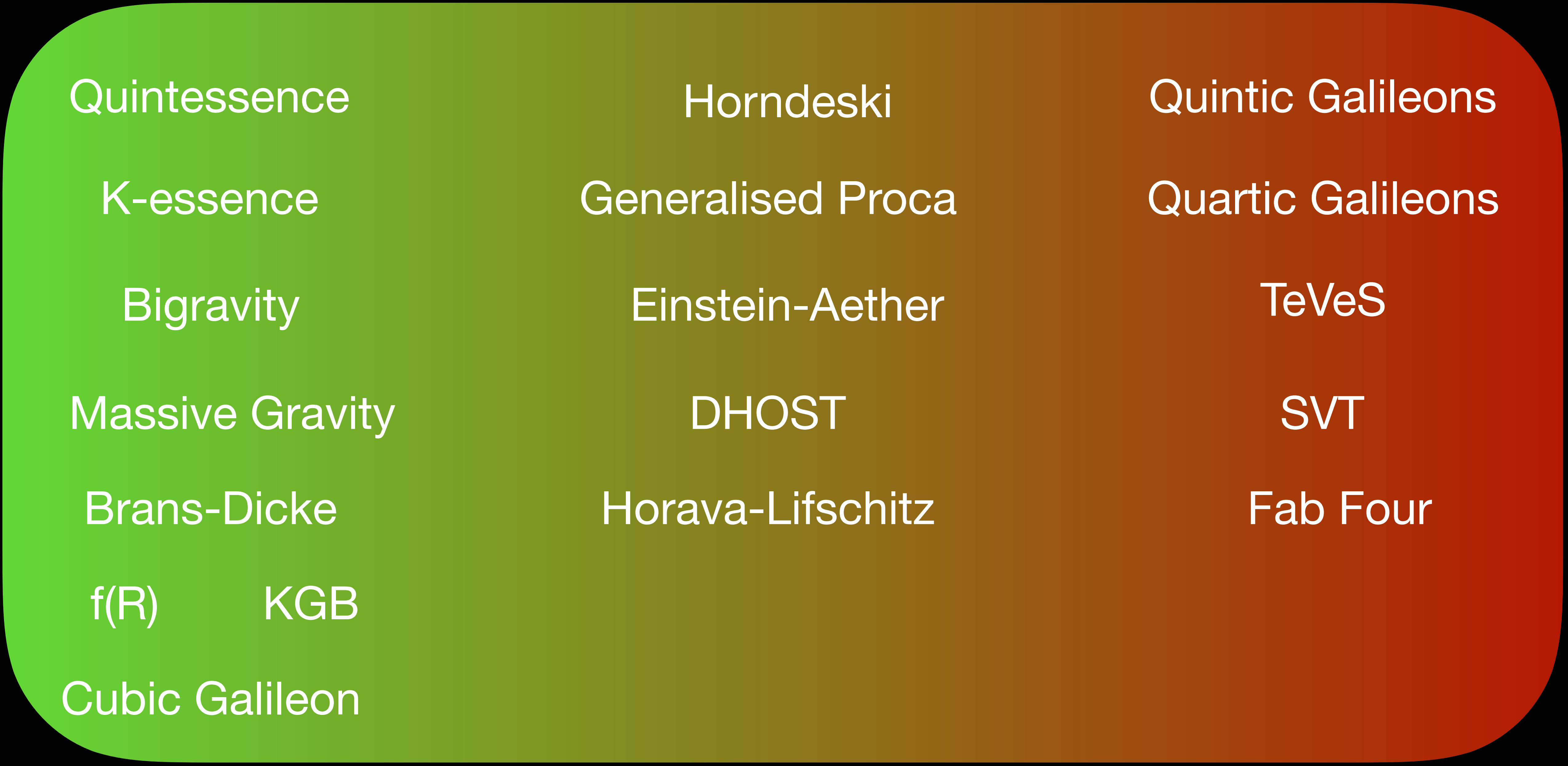
For bimetric theories, get a bound on graviton mass:

$$m_g \lesssim 10^{-22}\, eV$$

THE NEW THEORY LANDSCAPE



Quintessence

K-essence

Bigravity

Massive Gravity

Brans-Dicke

f(R)

KGB

Cubic Galileon

Horndeski

Generalised Proca

Einstein-Aether

DHOST

Horava-Lifschitz

Quintic Galileons

Quartic Galileons

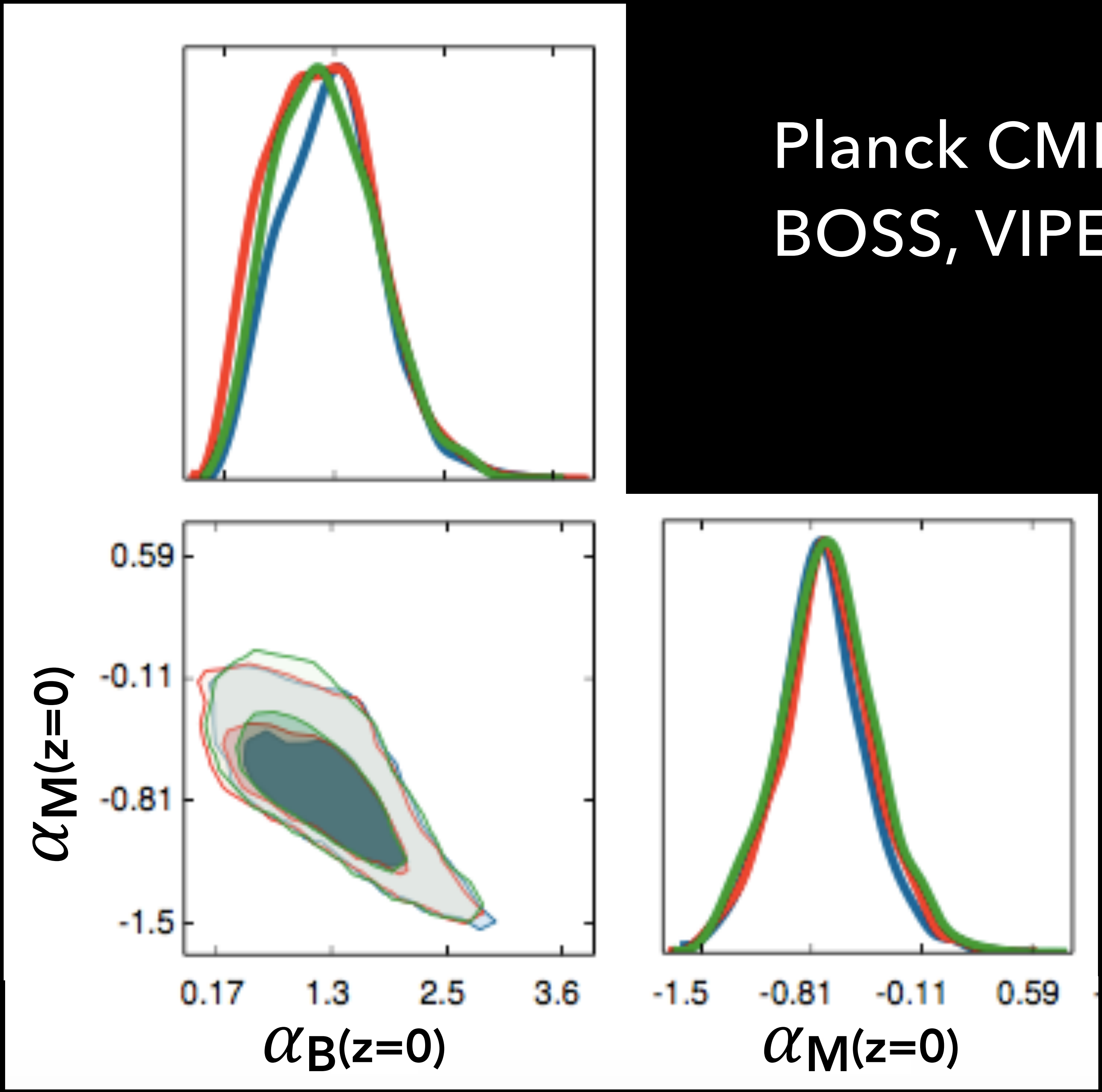
TeVeS

SVT

Fab Four

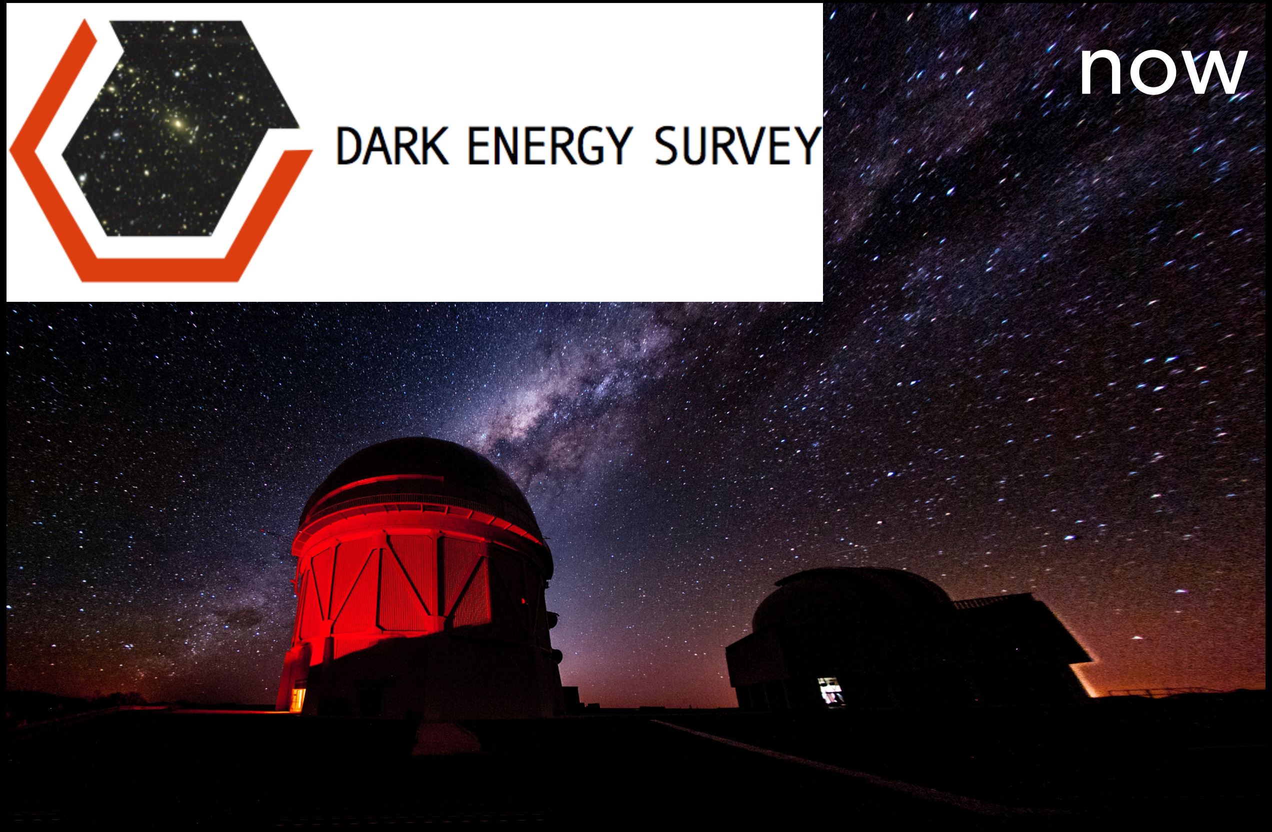
THE CURRENT STATE OF PLAY

Planck CMB data + galaxy surveys: BOSS, VIPERS, WiggleZ.

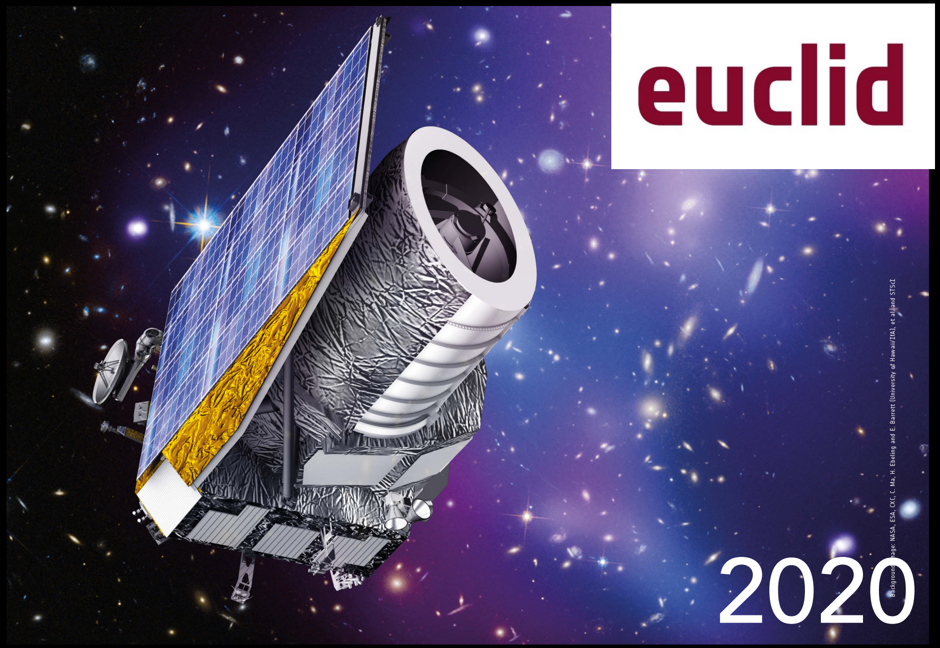


Bellini et al., 2015.

ONGOING & FUTURE EXPERIMENTS



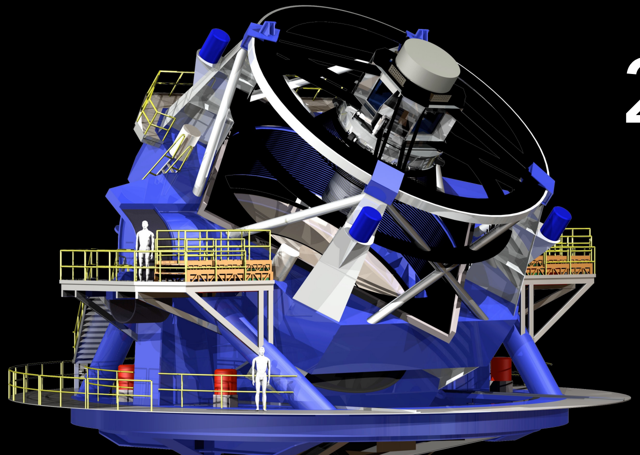
now



2020

LSST

Large Synoptic Survey Telescope



2021

2023

CONCLUSIONS

References:
1604.01396
1710.06394
(+1 in prep.)

tessa.baker@physics.ox.ac.uk

CONCLUSIONS

- The landscape of extensions to GR.

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CONCLUSIONS

- The landscape of extensions to GR.
- EFT-style model-independent treatment.

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CONCLUSIONS

- The landscape of extensions to GR.
- EFT-style model-independent treatment.
- $\boldsymbol{\alpha}_T(t)$ strongly constrained by GWs; others in progress.

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References:
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